Simple Mathematical Models for Estimating the Bio-Contamination Transported from a Lander or a Rover to the Martian Soil

Robert A. Beaudet.

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA, and Department of Chemistry University of Southern California, University Park, Los Angeles, CA 90089-0482

ABSTRACT

To enable reliable in situ, or sample return, life detection missions, it is critical that Mars Sample Return missions be free of any biological materials that originated from Earth. Therefore, it is important that likely cross-contamination mechanisms be thoroughly studied and understood.

Three simple models have been developed to estimate the maximum soil contamination that could originate from a bio-contaminated lander. All three models estimate the ground contamination concentrations at various distances from the lander. The first model estimates the ground concentration if the microorganisms covered the soil 360° around the lander. The second model uses a steady state Gaussian plume to transport the microorganisms from the Lander. The third model determines the ground contamination level from an instantaneous Gaussian puff release, probably at the time of landing.

Input to the models includes the total spacecraft (s/c) contamination level, the height of the lander, the size distribution of the particles, and their microbial burden, the fraction of the total contamination that is removed, the wind speed, and the diffusivities of the plumes. The results are given for input data available from old studies performed at the Kennedy Space Center. More realistic data are now being obtained at JPL.

INTRODUCTION

Background. Martian sample return (MSR) missions (MSR) will have very stringent requirements for both forward and backward planetary protection. Rovers will probably require Category IVb, and landers will have either Category IVa or IVb planetary protection requirements. Also, the NASA Planetary Protection Officer has set tentative requirements that any MSR mission must have less than a 0.01 chance of returning a terrestrial microorganism in a sample. This can be interpreted to mean that if there were one hundred missions to Mars only one of them would return a terrestrial microorganism in a sample.

One of the factors required to determine the required cleanliness level of the lander and rover is estimating the crosscontamination, that is, the number of microorganisms on the Lander and Rover that could be transported to Martian soil and that could be collected in the return sample. Then the required bioburden of the lander can be back-calculated. A fraction of the particulates on a lander will be tightly bound to the surface, and will continue to adhere to the surfaces under most Martian climates. While the fraction of microorganisms on the s/c that will be removed can not be readily estimated at this time, the maximum contamination levels can be estimated by using transport models to estimate the contamination of Martian soil from particulates dislodged from the lander or rover. Also, these models can be used to back-calculate the contamination levels required on the spacecraft to meet the requirements under the worst conditions. It must be noted that this model only estimates one phase of crosscontamination. It assumes that the contamination levels on the lander have not changed since it was assembled and cleaned/sterilized prior to launch. Any change in the bioburden that might occur during launch or during flight is not considered here.

Three simple mathematical models have been constructed for estimating this crosscontamination. These estimates can be refined, as better data become available. Also, the models can always be refined. We have used approaches developed originally for estimating nuclear fallout.[1] However, most of these models treat point sources. More recently, these same approaches have been used in air pollution and HAZMAT estimates. However, these models are usually more concerned with vapor dosages than particulates.

ASSUMPTIONS. The fundamental assumptions used in all our models are the following:

1. The lander is assumed to be a vertical line source with the particulates evenly distributed along its length. The relative number of particles in each size range is required.
2. All the microorganisms are attached to particulates of various sizes or are themselves small particulates. (The overall strategy is to model the *particulate* transport until the last step and then to use estimates of the number of microbes attached on particles of a given size to obtain the microbial contamination concentration.)
3. When the particulates are dislodged, they are transported by the Martian winds and settle at a terminal velocity determined by Stoke's equation. (The particulates in each size range are treated separately. The fraction in any size range that can be dislodged can also be given.)
4. Once they touch the Martian soil, the particulates remain there and do not migrate any farther. We do not consider any secondary transport of the particles once they land on the surface. Such secondary transport would spread the contamination farther from the s/c, but would also reduce the surface concentration.
5. It is conservatively assumed that the wind is sufficient to remove all of the particles in the duration of interest. No adhesion parameters are considered in the current models.

Our goal was to design the models on simple, readily available software platforms. Spreadsheets would have had the advantage that parameters can be changed easily as the input data are refined. Also, spreadsheets such as EXCEL are portable and widely available. Unfortunately, they did not have the capability to calculate Gaussian plumes and plot contour maps. So, the models were generated on MATHCAD, a software package that is readily available and easy to use on any PC.

Three models corresponding to different scenarios have been generated. Together, they bracket the contamination levels under different climactic conditions. The models, the scenarios and some sample results are described in this paper.

INPUT VARIABLES USED IN THE MODELS

LANDER CONFIGURATION

This section describes the input parameters with some typical values used in the models. These parameters can be changed to reflect the actual values for a given mission. Most parameters are linearly scalable. The Martian climactic variables are given in Table 1. The lander height and exposed surface area are required. We have assumed that a lander is approximately two meters high and about three meters in diameter. The total exposed contaminated surface area is approximately 100 m^2. In further refinements, the distribution along the length could be altered to reflect the true surface area at any given height.

BIO-BURDEN

The number of organisms attached to a particle and the particle size distribution are taken from old Kennedy Space Center studies performed during the Viking Program.[2] An experimental program is now being conducted to obtain better estimates of the microbial count on particles from an actual clean room environment and to estimate the particle adhesion.

The models calculate the ground contamination concentration for each particulate size range given in Table 2 by using the maximum size in each range. The size distribution of the particles from a cleaned surface and the number of organisms on each particle of a given size are also given in Table 2.[2] The distribution has been normalized to set the total contamination at the 300 spores/m^2 level. The total bio-burden is assumed to be ten times the spore level. Therefore, the total contamination level is 3000 microorganisms/m^2. For a surface area of 100m^2, the total bio-burden is 3.0×10^5, which are assumed to be distributed evenly over the length of the lander.

Table 1. The Martian Atmospheric Parameters used in the Model (*cf.* Ref. 3).

Gravitational acceleration on Mars	3.7 m/sec^2
Dynamic Viscosity of Martian atmosphere	1.305×10^{-5} kg/m-s
Density of the particles	2.0 gr/cc
Mean free path	4.47×10^{-6} m

TERMINAL VELOCITIES FOR THE MARTIAN ATMOSPHERE:

All models require the terminal settling velocities. These velocities are calculated for the Martian atmosphere[3] by using Stoke's theorem and Cunningham's correction for small particles.[4] For streamline flow and spherical particles, Stoke's Theorem is given by the following equation:

$$V_{t,Stokes} = \frac{g d_p^2 \rho_p}{18 \mu_g}$$

where

g = the Martian gravitational acceleration constant, 3.7m/sec^2;
d_p = the particle diameter;
ρ_p = the particle density
μ_g = the dynamic viscosity of the gas
$V_{t,\,Stokes}$ = the Stokes terminal velocity

This equation is accurate for particles with diameters between 5μ and 100μm. For the low gas densities found in the Martian atmosphere, Cunningham's correction is required for smaller particle sizes. The correction is given by the following expression:[4]

$$V_{t,d} = K_c \bullet V_{t,Stokes}$$

where

$$K_c = 1 + \frac{2\lambda}{d_p}\left[1.257 + 0.400\exp\left(\frac{-0.55 d_p}{\lambda}\right)\right]$$

Table 2. Particle size distribution and microbe concentration.

Particle size Range (micron)	Surface Conc. (particle/m^2)	Microbes per Particle	Microbe conc. (microbes/m^2)
5-10	1.09E+06	1.44E-03	1570.00
10-20	4.25E+05	2.35E-03	1000.00
20-30	8.14E+04	3.17E-03	258.00
30-40	2.48E+04	3.98E-03	98.60
40-50	9.65E+03	4.79E-03	46.20
50-60	4.38E+03	5.59E-03	24.50
60-70	2.21E+03	6.43E-03	14.20
70-80	1.21E+03	7.23E-03	8.75
80-90	7.06E+02	8.03E-03	5.67
90-100	4.32E+02	8.84E-03	3.82
100-200	8.60E+02	1.70E-02	14.60
200-300	4.84E+01	2.50E-02	1.21
300-400	7.16E+00	3.32E-02	0.24
400-500	1.66E+00	4.13E-02	0.07
Total:			3046

Table 3. Terminal velocities ($V_{t,d}$), time duration and distances required to reach terminal velocities.

Particle size microns	Stokes V_t (m/sec)	Cunningham's Correction	Corrected V_t (m/sec)	Time to attain V_t (sec)	Distance to attain V_t (m)
5	7.88E-04	3.63E+00	2.86E-03	7.74E-04	1.11E-06
10	3.15E-03	2.23E+00	7.02E-03	1.90E-03	6.66E-06
20	1.26E-02	1.58E+00	1.99E-02	5.37E-03	5.34E-05
30	2.84E-02	1.38E+00	3.91E-02	1.06E-02	2.06E-04
40	5.04E-02	1.28E+00	6.46E-02	1.75E-02	5.64E-04
50	7.88E-02	1.22E+00	9.65E-02	2.61E-02	1.26E-03
60	1.13E-01	1.19E+00	1.35E-01	3.64E-02	2.45E-03
70	1.54E-01	1.16E+00	1.79E-01	4.84E-02	4.34E-03
80	2.02E-01	1.14E+00	2.30E-01	6.21E-02	7.14E-03
90	2.55E-01	1.12E+00	2.87E-01	7.76E-02	1.11E-02
100	3.15E-01	1.11E+00	3.50E-01	9.47E-02	1.66E-02
150	7.09E-01	1.07E+00	7.62E-01	2.06E-01	7.84E-02
200	1.26E+00	1.06E+00	1.33E+00	3.60E-01	2.39E-01
300	2.84E+00	1.04E+00	2.94E+00	7.95E-01	1.17E+00
400	5.04E+00	1.03E+00	5.18E+00	1.40E+00	3.63E+00

and where λ is the mean free path of the gas:

$$\lambda = \frac{1}{\sqrt{2}\pi (N/V) d_p^2}$$

N/V is the molecular concentration in molecules per cubic meter.

The results are given in Table 3. Also, the time and the vertical distance that a particle travels before reaching terminal velocity are given. Only for the largest particles is the terminal velocity approximation not valid. Thus, the larger particles would settle more slowly than indicated by the values in Table 3. Thus, the time which is used in the models is $t=h/V_{t,d}$.

MODEL #1: ISOTROPIC DISPERSAL

SCENARIO

For the first model, we assumed the following scenario.

- The particles are removed from the s/c slowly by the Martian wind. Because the Martian wind changes direction through 360 degrees over the Martian day, these particles will be distributed uniformly in all directions around the lander.
- The particles are carried horizontally by the wind and settle with terminal velocities governed by the particle size according to Stokes Theorem. Thus, the larger heavier particles will settle faster than the smaller, lighter particles. The particles originating from the top of the lander will travel farther than those originating from the bottom.
- All microorganisms are assumed to adhere to the particles and are not transported independently.

Thus, the lander is considered to be a vertical line source uniformly emitting particles in all directions with microorganisms attached. On landing on the surface of Mars, a fraction (or all) of the particles are gradually dislodged and scattered in a horizontal radial direction. The contamination is uniform through 2π radians. The calculations are performed for particles of each given size range. The distances that the particles travel horizontally are determined by their height from the Martian ground and how long it takes the particles of the given size to settle according to Stokes equation. The settling time determines how far the particles of any given size range are carried horizontally. .

Simple ballistic calculations are performed. Then, the surface concentration of particles in each size range is determined. Finally, the total number of organisms at any distance from the lander is obtained by summing over the microbial content for each particle size range to yield the total microbe concentration.

CALCULATION OF THE GROUND CONCENTRATION OF PARTICLES.

The following variables have been defined for this model:

- h the vertical distance on the lander from the ground (meters).
- Ht= the height of the lander (meters).
- r = radial distance from the lander (meters).
- $v_{t,d}$ = terminal velocity (m/sec) for particles of a given size.
- u = horizontal wind velocity (m/sec).
- $C_{h,d}$ = the linear concentration of particles on the lander for any given particle size, d_p (part./m^2).
- $C_{r,d}$ the Martian surface concentration for particles of size, d_p at distance, r from the lander.
- $n_{d,}$ = number of microbes on particles of size d_p,.
- $N_{r,d}$ = total number of microbes originating from particles of size, d_p at distance, r from the lander.
- N_r = total microbe contamination concentration at distance, r from the lander

How far a particle of a size d_p travels is determined by the height of the particle and the terminal velocity, $V_{t,d,}$ determined by Stoke's equation given above. During this time, the linear distance traveled is $r = ut$. Therefore,

$$r = \frac{u}{V_{t,d}} h \quad \text{and} \quad \Delta r = \frac{u}{V_{t,d}} \Delta h$$

Thus, a segment Δh along the cylinder will contaminate a ring of width Δr at distance r from the lander. The segments must be varied from $h=0$ to $h=Ht$, the height of the lander. The height of the lander, Ht, determines the maximum distance from the lander that is contaminated by the particles of any given size. A particle mass balance requires that the particles in the height segment Δh must be uniformly distributed over the ring.

$$C_{h,d} \Delta h = C_{r,d}(2\pi r)\Delta r = C_{r,d}(2\pi r)\frac{u}{V_{t,d}}\Delta h$$

Solving for $C_{r,d}$,

$$C_{r,d} = \frac{C_{h,d}}{2\pi r}\frac{V_{t,d}}{u}$$

The surface microbial concentration, N_{rd}, resulting from particles of a given size is now easily calculated if we know the number of microbes per particle of size d, as a function of the particle size.

$$N_{r,d} = n_d\, C_{r,d}$$

and the total contamination concentration is obtained by summing over the fourteen particle size ranges.

$$N_r = \sum_{d=1}^{14} n_d C_{r,d}$$

RESULTS:

The model is amenable to simple spreadsheet software since the concentration is independent of the azimuthal angle. The data from Tables 1-3 were used in the calculation. Table 4 tabulates the microbe surface concentrations at seven wind speeds for various distances from the lander. Fig. 1 contains a log plot of the surface contamination as a function of distance from the lander.

GAUSSIAN DISPERSION MODELS

Simple Gaussian models for gas plumes and particulate settling have been developed by various organizations. The Department of Energy [then called the Atomic Energy Commission (AEC)] developed models to estimate the radioactive fallout from nuclear bomb tests.[1] The Army Chemical Warfare community was interested in predicting the aerosol dispersion patterns from bursting chemical munitions. More recently, the EPA has developed models for smokestack effluents and the risk assessment community has been interested in effluent dispersion from accidental releases of industrial chemicals. Most common models have been developed for point sources and gaseous emissions.

Table 4. Typical microbe surface concentrations (microbes/m^2) at various distances from the lander for the indicated wind speeds. The total contamination on the lander was 3.0 x 10^5 microbes.

	Wind speed (m/sec)						
Distance (m)	**1 m/sec**	**2 m/sec**	**3 m/sec**	**4 m/sec**	**5 m/sec**	**6 m/sec**	**7 m/sec**
0.5	1582.690	801.327	537.189	402.892	322.313	268.595	230.224
1	762.388	395.672	267.109	200.332	161.157	134.297	115.112
2	301.347	190.597	127.065	98.918	79.134	66.777	57.238
3	150.674	75.337	63.532	47.649	38.119	31.766	28.262
4	120.539	60.269	40.180	38.119	30.496	25.413	21.783
5	98.564	50.225	33.483	25.112	25.413	21.177	18.152
6	82.508	43.050	28.700	21.525	21.783	18.152	15.559
7	72.194	37.668	25.112	18.834	15.067	15.883	13.614
8	62.260	33.483	22.322	16.742	13.393	11.161	12.101
9	56.034	30.135	20.090	15.067	12.054	10.045	10.891
10	33.972	19.252	13.393	10.045	8.036	6.697	5.740
15	23.504	14.008	9.626	7.534	6.027	5.022	4.305
20	18.803	10.768	7.471	5.914	4.822	4.018	3.444
25	13.747	8.493	6.226	4.813	3.943	3.348	2.870
30	11.783	7.280	5.127	4.002	3.300	2.816	2.460
35	10.310	5.876	4.487	3.502	2.888	2.406	2.112
40	7.067	5.223	3.775	2.991	2.490	2.139	1.877
45	6.360	4.701	3.397	2.692	2.241	1.868	1.650
50	5.782	3.749	3.088	2.316	1.958	1.698	1.500
55	5.300	3.437	2.612	2.123	1.795	1.556	1.334
60	4.893	3.172	2.411	1.960	1.657	1.380	1.232
65	4.543	2.946	2.239	1.820	1.456	1.282	1.144
70	4.240	2.749	2.089	1.567	1.359	1.196	1.025
75	3.975	2.578	1.959	1.469	1.274	1.122	0.961
80	1.423	2.426	1.617	1.383	1.199	0.999	0.905
85	1.344	1.767	1.527	1.306	1.132	0.944	0.855
90	1.273	1.674	1.447	1.237	0.990	0.894	0.766
95	1.209	1.590	1.375	1.175	0.940	0.849	0.728
100	0.806	1.060	0.707	0.687	0.550	0.522	0.448
150	0.605	0.302	0.530	0.398	0.412	0.344	0.295
200		0.202	0.134	0.265	0.212	0.177	0.196
300		0.151	0.101	0.076	0.159	0.133	0.114
400			0.081	0.060	0.048	0.040	0.091
500			0.067	0.050	0.040	0.034	0.029
600				0.043	0.035	0.029	0.025
700				0.038	0.030	0.025	0.022
800					0.027	0.022	0.019
900					0.024	0.020	0.017
1000							

We have generated two Gaussian dispersion models. The first uses a continuously emitting line source, which produces steady state concentrations of effluents in a plume. This model is comparable to slow erosion of the particulates on the lander by the Martian wind that is always in the same direction. The second model uses a puff. This model describes an instantaneous release of the contamination on the lander. In both of our models, the line source is generated by integrating over the height of the lander to form a line source. The calculations are performed for each particle size range and are summed to produce the final results. The models are described in detail below.

MODEL #2: STEADY STATE GAUSSIAN DISPERSION MODEL

SCENARIO

In this scenario, the particulate contamination is assumed to emanate from the lander over its whole length very slowly and to form a plume in one direction governed by the Martian winds. Because the contamination is swept slowly from the lander, a continuous plume of constant concentration is formed.

GENERAL APPROACH

This scenario is comparable to a "smokestack model" used in air pollution. The settling velocity is taken into consideration by correcting the horizontal centerline of travel of the plume to slant downwards with the proper settling velocity for each particulate size range. The plume disperses in a Gaussian distribution. The original equations are described in Wark and Warner.[6] However, they have been modified to model a line source instead of a point source, and surface concentrations have been summed to account for all the various particulate sizes.

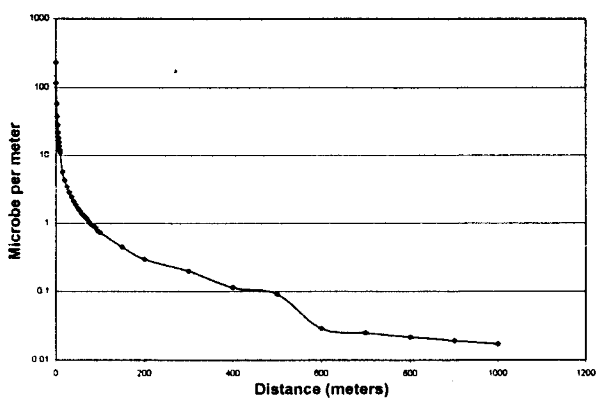

Fig. 1. Microbe contamination (microbes/m^2) versus distance (m) for an isotropic dispersion. The irregularities originate from the discrete nature of the summation.

The coordinates are chosen such that z is the vertical distance above ground level; x is the direction at which the plume's centerline travels; and, y is perpendicular to x and z. Then the basic equation for the microbe concentration, N(x,y,z,d,h) for the particles of size, d, dislodged from a height h are given by

$$\boxed{N(x,y,z,d,h) = \frac{Q_d}{2\pi u \sigma_y \sigma_z} \exp\left\{ -\frac{1}{2}\left[\frac{y}{\sigma_y}\right]^2 - \frac{1}{2}\left[\frac{z - h + \left(x \cdot v_{t,d}/u\right)}{\sigma_z}\right]^2 \right\}}$$

where the variables are defined as:

h = the height in the z-direction at which the particles are released the lander (m)

H_t = the height of the lander

Q_d = the total emission rate of microbes from particulate of diameter d from the lander at height h, *multiplied* by a long duration such that Q_d is the total number of microbes dislodged per unit height. (number of microbes/m-)

u = the wind speed in the x-direction

$v_{t,d}$= terminal velocity (m/sec) for particles of diameter d obtained from the corrected Stokes equation

D_g = diffusivity in the direction g $(g=x,y,z)$. (m^2/sec)

σ_x, σ_y, σ_z = the dispersion coefficients in the x, y and z directions (m).

$w(x,y,d,h)$ = the deposition rate at x,y for particles of size d from height, h, given in microbes/m^2-sec

t = time (sec)

The dispersion coefficients, σ_g, increase with x, the distance traveled, and depend on the diffusivity of the atmosphere. They are given by

$$\sigma_x = \sqrt{2D_x t} \qquad \sigma_y = \sqrt{2D_y t} \qquad \sigma_z = \sqrt{2D_z t}$$

In the steady state treatment, x/u can be substituted for the time, t:

$$\sigma_y = \sqrt{\frac{2D_y x}{u}} \qquad \sigma_z = \sqrt{\frac{2D_z x}{u}}$$

The diffusivity D_x, in the direction of travel is ignored in steady state models.

On Earth, the dispersion coefficients, σ_x, σ_y and σ_z, are between 5-10 m at 100 m from the source for stable atmospheric conditions. Thus, the diffusivities, D, have values of about 3-6 m^2/sec. However, on Mars, the diffusivity has been estimated to be between 2,000 and 20,000 m^2/s.[5] These values were estimated from the dust patterns observed in photos taken by Mariner. If this is correct, the plume will be very widely dispersed, and it should disperse very rapidly, thereby diluting the surface microbe concentration rapidly with distance from the lander. However, these values seem to be disproportionately large. One explanation for such large values might be that the plumes accumulated over a long period of time. The wind direction varied during that time interval, leading to wider plumes than would have been expected based on simple diffusivities. Thus, these large values might not apply to the contamination dislodged from a lander over a short time scale. In the sample calculations performed here, the diffusivities have been set at 6 and 100 m²/sec.

The deposition rate of particles settling on the surface are obtained by multiplying the concentration at z=0 by the settling rate, v_d:

$$w'(x,y,d,h) = v_{t,d}C(x,y,0,d,h)$$

By using dimensional analysis, we see that w has units of microbes/m²-sec:

$$\left(\frac{m}{\sec}\right)\left(\frac{Microbes}{m^3}\right) = \frac{microbes}{m^2\ \sec}$$

In our treatment, to describe the lander as a line source, the equation is integrated over the height of the lander. MATHCAD evaluates the integral analytically by using error functions.

$$w''(x,y,d) = \int_0^{Ht} w'(x,y,d,h)dh$$

Finally, to obtain the total deposition rate the equation is summed over all the particle size ranges denoted by the index d.

$$w(x,y) = \sum_{d=1}^{14} w''(x,y,d)$$

The deposition rate along the centerline is obtained by setting $y = 0$.

$$N(x,0,0,d,h) = \frac{Q_d}{2\pi u\sigma_y\sigma_z}\exp\left\{-\frac{1}{2}\left[\frac{h-(x\cdot v_{t,d}/u)}{\sigma_z}\right]^2\right\}$$

Then, the surface concentration along the centerline is given by:

$$w(x,0) = \sum_{d=1}^{14}\frac{Q_d v_{t,d}}{2\pi u\sigma_y\sigma_z}\int_0^{Ht}\exp\left\{-\frac{1}{2}\left[\frac{h_n-(x\cdot v_{t,d}/u)}{\sigma_z}\right]^2\right\}dh$$

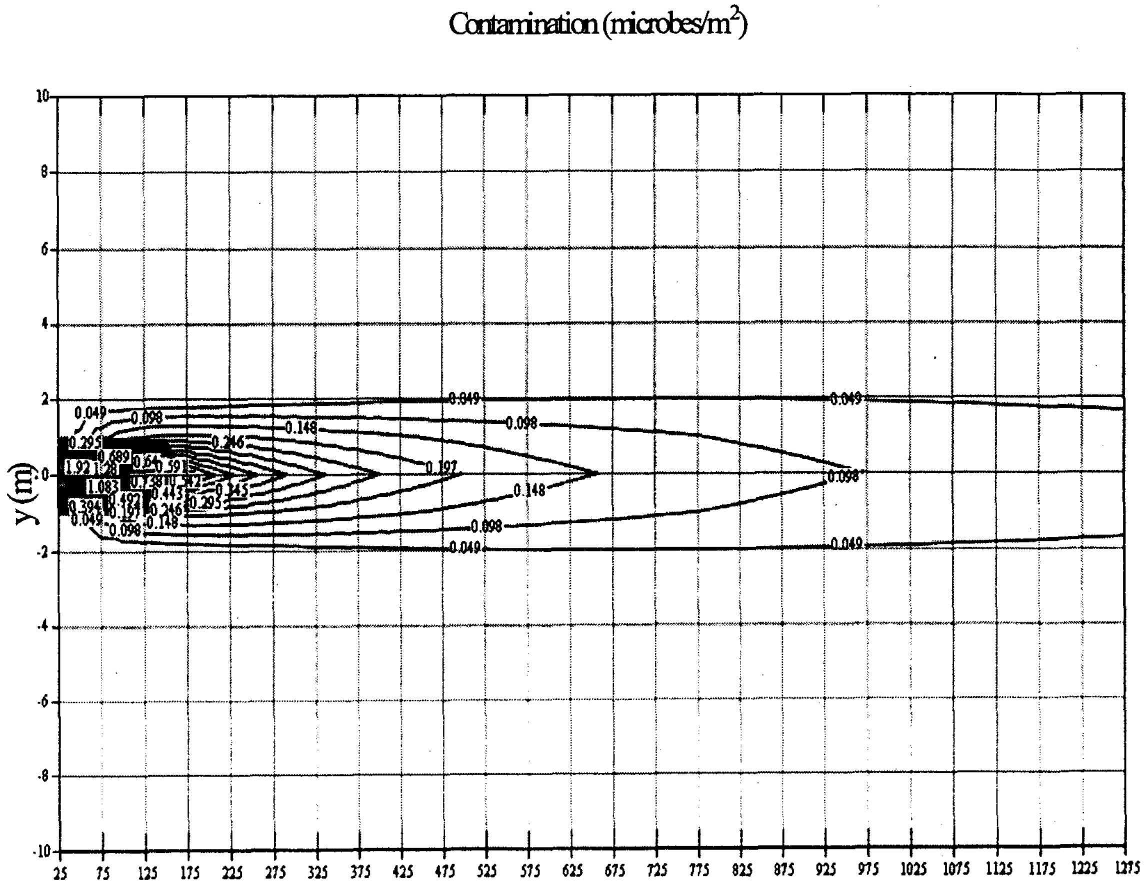

Fig. 2. Contour plot for the steady state model with the following values: wind speed = 7 m/sec, diffusivities, $D_y = D_z = 6$ m²/sec for 25 m<x<1275 m.

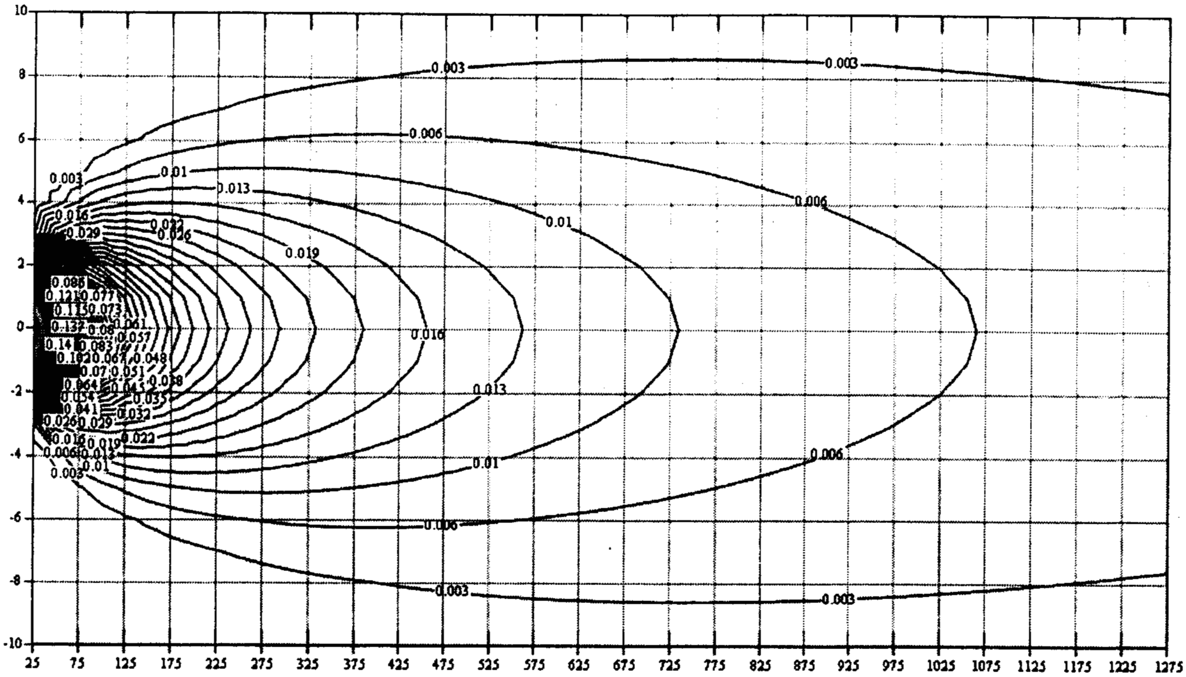

Fig 3. . Contour plot for the steady state model with the following values: wind speed = 7 m/sec, diffusivities, $D_y = D_z = 100\ m^2/sec$ for $25\ m < x < 1275\ m$.

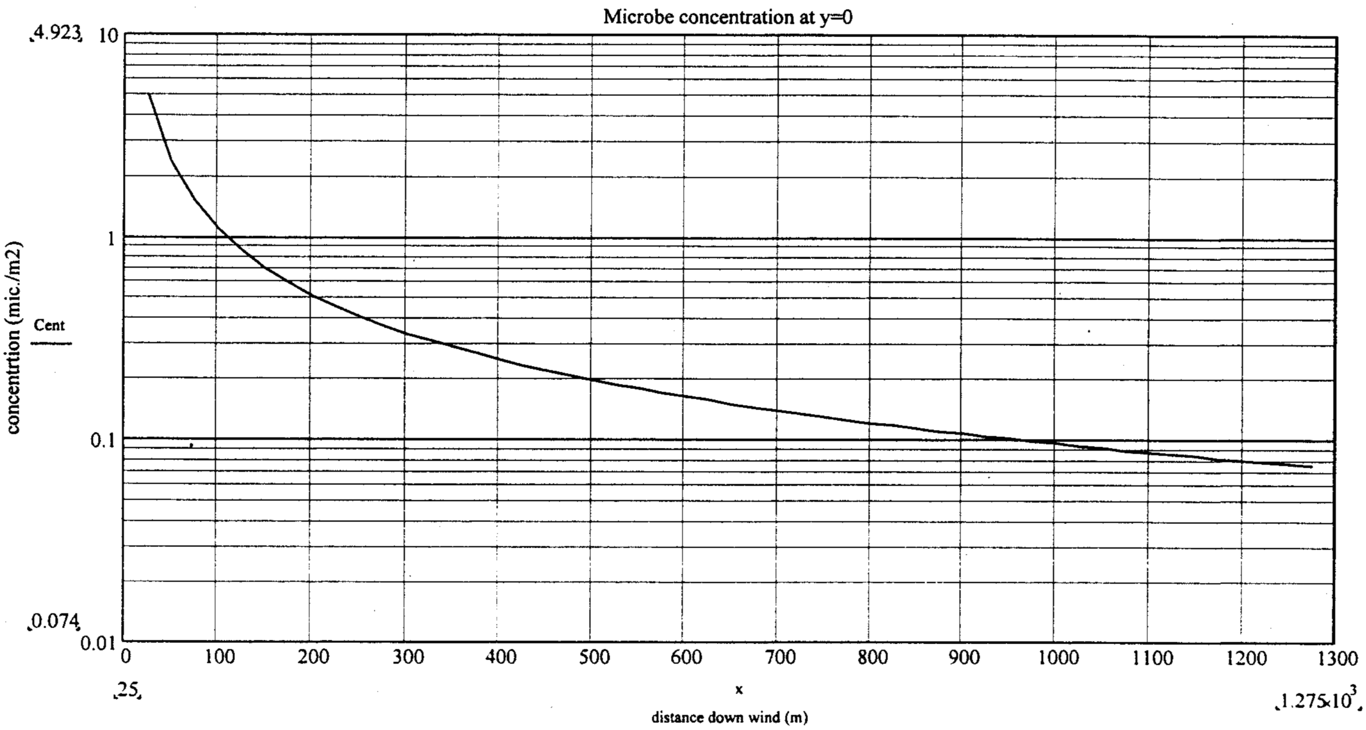

Fig 4. Contour plot of the contamination along the centerline of the plume obtained from the puff model. Input parameters are the same as those used in Fig. 2, wind speed = 7 m/sec, $D_y = D_z = 6\ m^2/sec$.

Some typical contour plots, isopleths, are given in Fig. 2 and Fig. 3. Fig 2 plots the surface microbe concentration from the lander to 1250 m for a plume traveling at 7 m/sec. with diffusivities of 6 m^2/s in the *y* and *z* directions. Fig. 3 depicts the contour plot when the diffusivities are increased to 100 m^2/sec. The surface concentration along the centerline of the plume is plotted in Fig. 4 for the same data as in Fig. 2.

$$w(x,0) = \sum_{d=1}^{14} \frac{Q_d v_{t,d}}{2\pi u \sigma_y \sigma_z} \int_0^{Ht} \exp\left\{ -\frac{1}{2} \left[\frac{h_n - (x \cdot v_{t,d} / u)}{\sigma_z} \right]^2 \right\} dh$$

Note that the equation has a mathematical singularity at x=0. Thus, all plots run from positive x value.

RESULTS

MODEL #3: PUFF GAUSSIAN DISPERSION MODEL

SCENARIO

In this scenario, it is assumed that the particles with the microbe contamination leave the lander very rapidly after the lander hits the ground, induced, for example, by the landing shock. Thus, a "puff" is formed which disperses and expands according to a *three*-dimensional Gaussian model.

APPROACH

This model is very similar to the steadystate model. The center of the cloud travels in the *x*-direction at the Martian wind speed. However, it also expands in the x-direction, unlike the steady state model. The cloud center also settles with the terminal velocity for each particle size. All the particles in the cloud finally settle on the ground. The time evolution for the concentration of particles (microbes/m^3) in the cloud is represented by the following equation:

$$N(x,y,z,d,t) = \frac{1}{(4\pi)^{3/2}(D_x D_y D_z)^{1/2} t^{3/2}} Q_d \int_0^{Ht} \exp\left[\frac{-(z-h+v_{t,d}t)^2}{4D_z t} - \frac{(x-ut)^2}{4D_x t} - \frac{y^2}{4D_y t} \right] dh$$

The exponential term in *z* represents the settling of the cloud center with time as described above, while the *x* term describes the horizontal motion of the cloud in the *x*-direction carried by a wind with velocity, *u*. The y term describes the dispersion of the cloud in the perpendicular direction.

Note that the diffusivities are time dependent and are included directly in the equation. Also, note that the concentration is now a function of *t* because this is not a steady state equation. The concentration at any (x,y) changes with time as the cloud passes by the point. Unlike the continuous model described above, the source, Q_d has units of microbes, and C(x,y,z,t) has units of microbes/m^3. The distribution is summed over the fourteen particle size ranges as in the previous model.

The concentration at the surface is given by setting *z=0* in the above expression.

$$N(x,y,0d,,t) = \frac{1}{(4\pi)^{3/2}(D_x D_y D_z)^{1/2} t^{3/2}} Q_d \int_0^{Ht} \exp\left[\frac{-(h-v_{t,d}t)^2}{4D_z t} - \frac{(x-ut)^2}{4D_x t} - \frac{y^2}{4D_y t} \right] dh$$

To obtain the deposition rate, *C(x,y,0,d,t)*, is multiplied by the settling velocity, $v_{t,d}$, as we did before, and summed over all the particle size ranges.

$$w'(x,y,t) = \sum_{d=1}^{14} N(x,y,0,t) v_{t,d}$$

The total deposition at position (x,y) is given by numerically integrating *w'(x,y,t)* over time.

$$w(x,y) = \int_{t\min}^{t\max} w'(x,y,t)dt$$

Ideally, w'(x,y,t) should be integrated from *t= 0* to infinity at every point *(x,y)*. However, to speed the calculations, the integration limits are selected to begin integrating three "sigmas" before the cloud arrives at any point and to continue integrating for three "sigmas" after the cloud center has passed the point, *(x,y)*.

An array M(x,y) with a specified number of rows and columns that span the area to be plotted is calculated. Normally 30 to 50 points in each direction is adequate to produce a smooth contour. The points must be equally spaced in x and y. This spacing is also selected and it determines the range of the plot. This array is used to generate a contour plot automatically by the program. Unfortunately, MATHCAD provides little choice at selecting the values at which the contour lines are plotted. Because MATHCAD does not save any calculations when the program is exited, the calculations must be repeated each time. To alleviate this problem, the arrays are exported in an *.xls* format for later use and archiving. On a 450MHz AMD K-6 PC, a run calculating a 50 x 50 array requires 30-45 minutes. The program can also plot instantaneous contours in the *(x,y)* and *(x,z)* planes, as well as surface contamination levels along the center line.

All models have been validated by obtaining mass balances. The deposition function w(x,y) has been integrated over all space to demonstrate that all the microbes released from the source are deposited on the surface, and are accounted for. The results have also been compared to those from the Steady State Model.

RESULTS

Fig 5 depicts contour plots with the same input data as Fig. 2. However, the scale has been enlarged to depict the contours close to the lander. Note that there is now contamination on the upwind side of the lander. Since no diffusion in the x-direction was included with the steady state model, it was not possible to predict if any contamination would diffuse upwind. In the puff model, which is more realistic, the diffusion along the direction of travel is also included. Thus, some particulates will diffuse upwind from the lander even in a 7 m/sec wind.

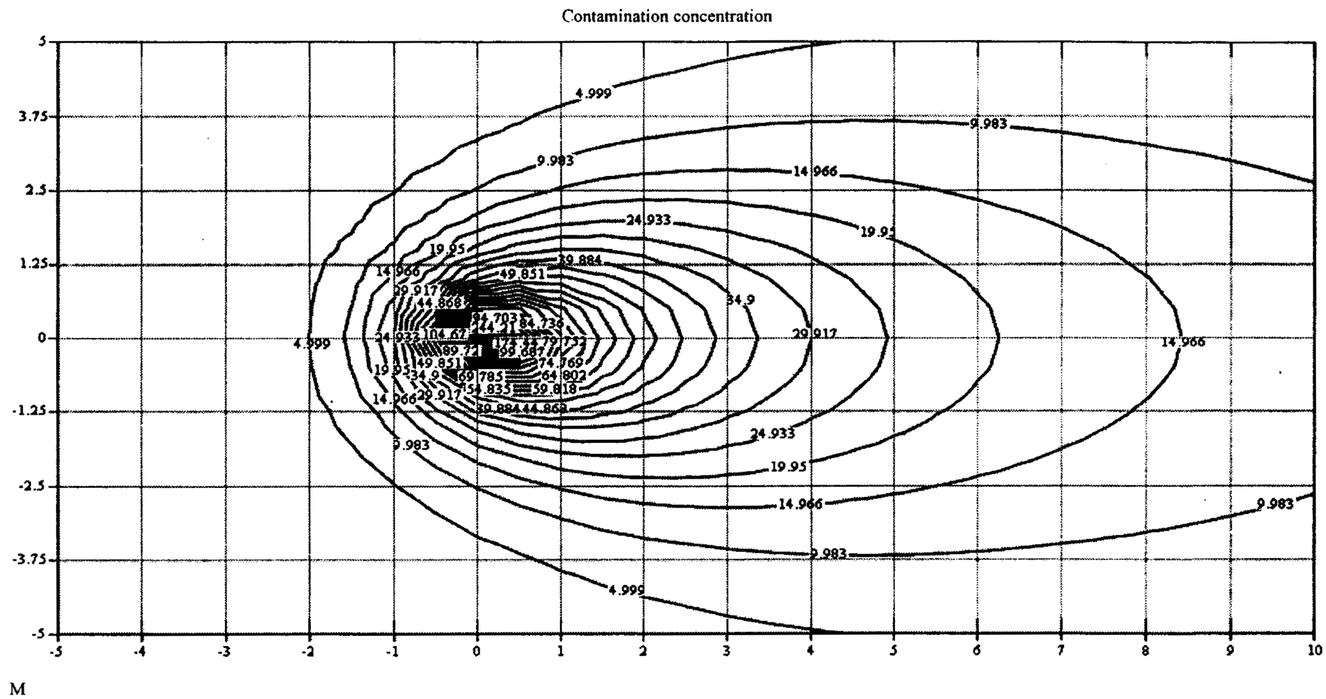

Fig. 5. A typical contour plot for a puff dispersion with the same parameters as in Fig. 2. Note that the contamination spreads to the upwind side of the lander.

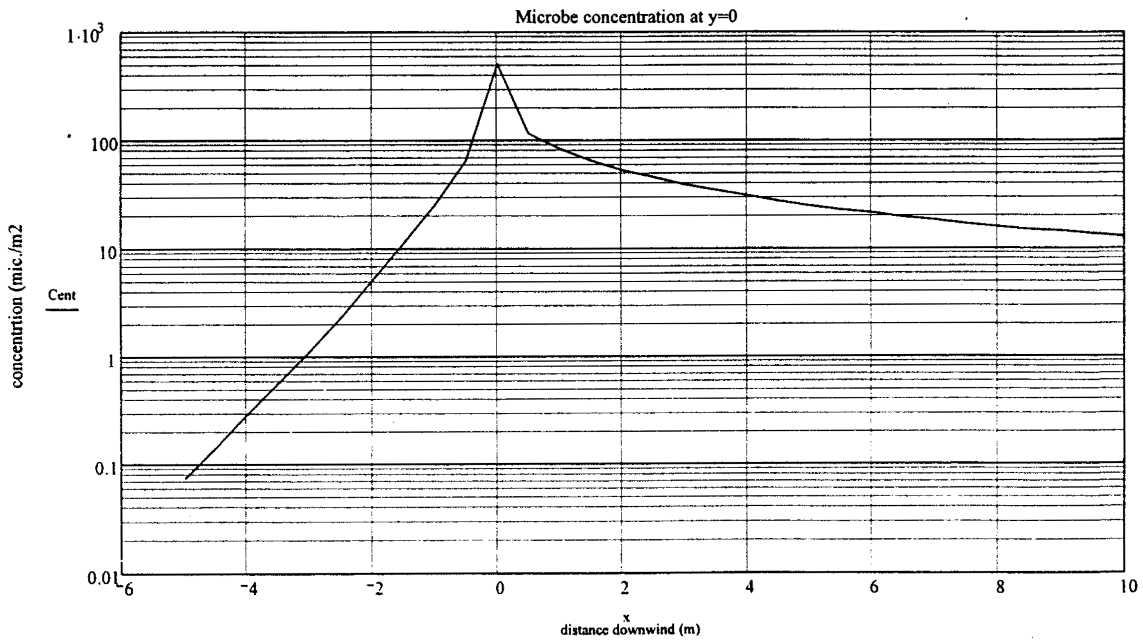

Fig. 6. A plot of the surface contamination along the centerline at y=0. This shows again that there is some contamination upwind of the lander.

CONCLUSION

Simple models can estimate the contamination levels that could be transported from a lander to the Martian soil under various conditions. At this time, the notorious dust devils have not been modeled.

The models with the input parameters that we have used provide a very pessimistic worst case analysis. To obtain more reasonable estimates will require improved information on the following factors:

- Better knowledge of the actual Martian climactic conditions including wind speeds, dust storms, etc. Dust storms could erode contamination from the surfaces, which would not be removed under milder conditions. The model is very sensitive to the actual diffusivities in a Martian atmosphere.
- Better knowledge of the actual contamination on the lander and rover *after* landing. The launch, orbiting and the landing conditions can change the actual bioburden after the spacecraft is assembled, cleaned and assayed at the Kennedy Space Center. The large forces exerted at launch and landing may cause recontamination from other modules that were not cleaned to the same levels as the lander and rover.
- The probability or the fraction of particulates that will be removed under various conditions. This factor is very dependent on particle size. Small particulates are known to be more tightly bound to the surfaces than larger particles. Large particles settle much faster than the small particles. Everyone has experienced that a dirty automobile driven at seventy miles per hour is still dirty after being driven for hours.

The Planetary Protection Program at JPL has studies underway to better estimate the adhesion forces of particulates on surfaces and the number of microorganisms to be expected on particles of different sizes in environments similar to the assembly facilities.

ACKNOWLEDGMENTS

The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Also, I acknowledge the assistance of Dr. Ram Manvi for providing references and pointing this work in the right direction. I also thank Dr. Jack Barengoltz for providing the data from the old Viking work on the particulate distribution given in Table 2 and for many helpful discussions.

REFERENCES

1. D. H. Slade, ed., Meteorology and atomic energy, TID-24190, Washington, D. C., 1968.

2. J. Barengoltz, private communication.

3. H. H. Kieffer, B, M. Jakosky, C. W. Snyder and M. S. Matthews, Eds. Mars. University of Arizona Press, Tucson, 1992, pp28ff.

4. Kenneth Wark and Cecil F. Warner, Air Pollution: Its origin and Control. New York, Harper and Row, 1981, 2nd Ed. pp.166ff

5. F. A. Gifford, R. P. Hosker, Jr., and K. S. Rao, Icarus **36,** 133 (1978).

CONTACT

Robert A. Beaudet is a professor of physical chemistry at the University of Southern California. He is also associated with JPL as a member of the Planetary Protection Group. His permanent university address is Department of Chemistry, Seaver Science Building Room 622, Los Angeles, CA 90089-0482. His email address is beaudet@chem1.usc.edu at the university or at JPL, Robert.A.Beaudet@jpl.nasa.gov.